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Hydrogen Infrastructure - Efficient Risk Assessment and Design Optimization Approach

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With the ambition to cut emissions from transport hydrogen fuelled vehicles and marine vessels are now being introduced several places in the society. To support this development there is a need for infrastructure to produce and transport gaseous and liquid hydrogen. The properties and safety challenges related to the use of hydrogen are very different from those of conventional fuels, thus safe design solutions may require unconventional solutions. Hydrogen has extreme properties in many ways. It is buoyant when in gas phase while a liquid hydrogen spray will develop a dense plume. The reactivity is higher, flammable range wider and the ignition energy lower than for conventional fuels. Flames may be invisible and radiation is low. When performing risk assessments for land planning purposes, bunkering assessments or passenger and crew safety these aspects must be reflected. Properties like the positive buoyancy, strong dilution for sonic releases into air, and a low reactivity and energy content for concentrations below 10% must be exploited during design to ensure acceptable risk levels. In this article a two level risk assessment and design assistance approach is presented in which risk screening with rapid consequence calculations and frequency assessments for release, dispersion, fire and explosion are performed during design review with indicative hazard distances estimated. Possible risks of concern are in this way identified, and design can be adjusted or mitigation measures introduced. When required more accurate CFD calculations are thereafter performed for more precise consequence estimates. The risk assessment approach will be described with examples illustrating the approach.

1. Introduction

In the years 2005-2010 there were numerous R&D initiatives looking into the use of hydrogen as a zero emission fuel for cars and buses, and safety aspects were evaluated in projects like HySafe and in IEA Hydrogen Implementation Agreement expert groups. Most projects in this period had the character of strongly subsidised demonstration activities, and many players had doubts whether hydrogen would have a role in the future low emission society due to challenges with storage density and price. A stronger dedication from authorities for emission cuts and competition towards offering competitive zero emission solutions seem to have sparked a new hydrogen wave from 2015 and onwards, this time many of the projects seem to have a more commercial character, and developments are seen to facilitate energy demanding transportation on land (trucks and trains) and sea (fast passenger vessels, car ferries and eventually cruiseships), including green and carbon neutral production facilities and distribution/supply. In order to support this development a good understanding of the safety aspects of hydrogen is required, including the ability to efficiently and accurately estimate possible risks and give recommendations for risk reduction measures

1.1 Hydrogen properties relative to methane

Being the first element hydrogen properties are in many ways extreme, see Table 1. To optimize safety while ensuring cost efficient solutions it is important to exploit inherently safe properties of hydrogen, like strong buoyancy and low reactivity and energy at concentrations less than 10-15%, while preventing accumulation of hydrogen at more reactive concentrations within congestion or confinement. For the best results safe design should be in focus from the start.

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Table 1: Some relevant hydrogen properties compared to methane

Property	Methane	Hydrogen	Comment hydrogen vs methane
Flammable range in air	5-15%	4-75%	7x wider
Maximum burning velocity	0.4 m/s	2.7 m/s	6x higher
Minimum ignition energy	0.29 mJ	0.017 mJ	15x lower minimum ignition energy
Detonation energy	1000 g TNT	1 g TNT	1000x lower, DDT is a real concern for H_2
Density relative to air	0.55	0.07	8x lighter
Sonic speed	460 m/s	1290 m/s	2.8x higher release velocity
Stoichiometric in air	9.5%	29.5%	3x higher
Combustion energy LFL	0.5 MJ	2 MJ	4x lower
Boiling point	111 K	20.4 K	LH2-sprays will freeze O_2 and N_2 in air
Density at BP relative to air	1.5	1.03	LH2 sprays dense due to air cooling

2. Risk assessment approaches

Hydrogen risk assessment methodology varies with application and jurisdiction. Some typical approaches are:

Safety distances	For refueling stations or other standardized installations some jurisdictions operate with standard safety distances. The main advantage is an efficient permitting process for standard installations, while non-standard layout or simultaneous operations may lead to a more tedious permitting process.
Credible approach	'Credible' accident scenarios are assessed and safety distances defined based on these. This approach will to a greater extent reflect local conditions (pressures/pipe dimensions) and can facilitate a smooth permitting process. Major disadvantages are variation in interpretation of the term 'credible', and that (assumed) low frequency high consequence scenarios are not assessed.
Probabilistic study	All accident scenarios are assessed with frequency and consequences. Distances to various fatality frequencies (often 10^{-5}/y, 10^{-6}/y, 10^{-7}/y in Seveso-directive studies), costs or frequency of barrier failure may be estimated. Main advantages are flexibility regarding layout and simultaneous operations. Low frequency high consequence events are assessed, giving insight in uncertainties and mitigation. Approach requires more extensive assessments and competence by risk specialist and authorities.

In this article the main focus will be on the probabilistic risk approach assessing expected frequency and potential consequences of any hydrogen loss of containment event with consequences of concern. The first steps of the analysis may be to describe the hydrogen systems and identify major hazards (HAZID). To facilitate an efficient permitting and design process risk reduction philosophies and recommendations are brought up already during the HAZID workshop. Risk acceptance criteria for the relevant installation should be identified, and the risk thereafter estimated:

$$\text{Risk} = \Sigma(\text{frequencies x consequences}) \qquad \text{sum over all loss of containment scenarios} \qquad (1)$$

There will be significant uncertainties in the many steps and assumptions of a risk assessment, in particular related to scenario frequencies, but also on the consequence modelling for a given scenario. One important part of the risk assessment should be to discuss uncertainties, and recommend and/or assess risk mitigation measures (e.g. ALARP), in particular for situations where risk acceptance criteria are not met.

2.1 Frequencies

To estimate representative event frequencies is a challenge in probabilistic risk assessments. Uncertainties in frequency estimates can be expected to be higher for hydrogen systems than within existing industries due to fewer implemented systems and shorter experience. Frequencies for hydrogen are generally based on oil and gas industry experience, but with some adjustments to reflect aspects of hydrogen systems such as very high pressures, possible hydrogen embrittlement mechanisms, and a generally robust design. The typical approach is to perform equipment counts of the hydrogen systems to find frequency distribution of hole sizes, and derive a leak rate distribution taking pressures into consideration. Common sources for frequencies are HSE (2012), de Haag and Ale (1999) and Groth et al. (2017), which in most cases recommend consistent frequencies.
The value of a probabilistic risk assessment can be good even if frequencies may be uncertain. As long a there is a reasonable distribution of frequencies among equipment types and diameters the risk assessment can help optimize the layout and minimize the risk for major consequence events. Where precision in risk

estimates is critical, and conclusions could change significantly if frequencies were underestimated, it is recommended to evaluate high consequence events carefully to see if these can be prevented or mitigated.

2.2 Consequence modelling

The small hydrogen molecule combined with the high stoichiometric concentration will in many ways simplify the consequence modelling for pressurized hydrogen releases. Pressurized hydrogen releases will tend to establish plumes barely influenced by buoyancy or wind within the reactive zone, and their characteristics, both regarding fire heat loads and dispersion distances, can be established for releases not interacting with obstructions/structures. The LR safety screening tool, see Figure 1, so far includes the following models:

- Hydrogen transient outflow models taking compressibility factor into account
- Distances to 4%, 8% and 15% concentration (NFPA-2 (2016)), flammable and explosive cloud volumes
- Assumed ignition probability and jet fire radiation along and across release (NFPA-2)
- Pressure and impulse with distance from catastrophic failure of pressurized tanks/vessels
- Explosion loads with distance (deflagration and detonation) using TNO-Multienergy method

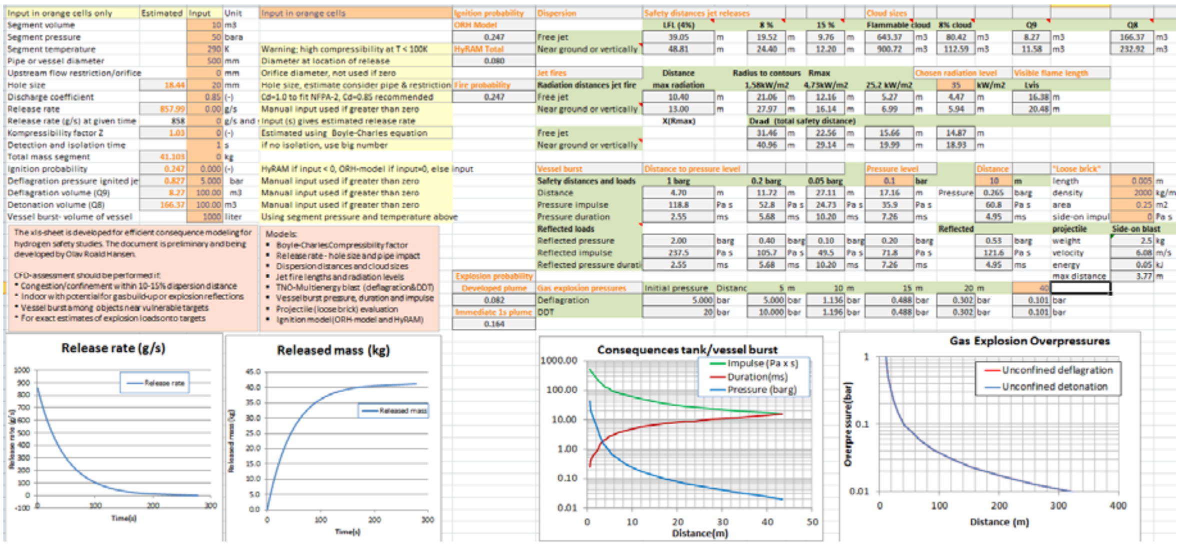

Figure 1: LR's excel based H_2 safety screening tool predicting transient outflow, ignition probability, dispersion distances and cloud volumes, fire radiation loads, blast from vessel burst and deflagrations/detonations

In many cases these simplified models can be sufficient to establish a conservative consequence prediction from a hydrogen loss of containment scenario, and these models are used for the initial screening analysis. In cases where a release will interact with obstructions or confining structures prior to being diluted below 10-15%, in particular for indoor scenarios where gas cloud accumulation is possible, and for LH2 dense gas dispersion scenarios, more advanced CFD-modelling may be required to accurately predict dispersion and explosion phenomena, see e.g. Middha et al. (2009) and Middha et al. (2010). In Figure 2 one comparison between CFD and TNO-Multienergy method is shown predicting blast loads from an elongated 2600m^3 building. An absolute worst-case scenario is assessed with building filled with H_2 which detonates. Using the TNO-Multienergy model (implemented in LR screening tool) an idealized hemispherical gas cloud is assumed as source and 100 mbar blast contours extend 120m. If the detonating gas cloud in the actual elongated building is modelled with CFD the predicted blast waves are stronger in the lateral direction (100 mbar at 150m) than along the building axis (100 mbar at 105m). The detonation simulation was performed as described in Hansen and Johnson (2015). The CFD calculation can also predict blast wave interaction with buildings and structures. For catastrophic vessel burst similarly good first estimates can be found with screening tools (see Figure 1), while better precision and location specific load details can be obtained using CFD in which vessel shape, orientation and blockage by surrounding objects can be taken into account.

2.3 Vulnerability and fatality risk

The fatality risk thresholds generally used in risk assessments are influenced by past hydrocarbon experience from oil&gas and process industries, see e.g. OGP (2010). This will in many cases lead to excessive conservatism if directly applied to hydrogen scenarios, and for some criteria adjustments should be considered for hydrogen, see Table 2.

Table 2: Vulnerability/fatality thresholds which should be considered adjusted for hydrogen systems

Hazard	Fatality criteria	Need for adjustment for hydrogen scenarios
Blast pressures	~0.2-0.5 bar	Duration of blast load will be much shorter (2-20ms) than for hydrocarbon scenarios (20-250ms), duration should be considered assessing vulnerability to people and structures
Flashfire	LFL	People trapped in hydrocarbon flashfire (~1300˚C at LFL) are assumed fatally injured. At hydrogen LFL (4%) flames will only burn upwards, 8% concentration is required to burn sideways and downwards. Flame temperatures for these concentrations are low (370-700˚C). The fatality limit for hydrogen flashfires should rather be 8% than 4% (LFL).
Jetfire	~12.5 kW/m^2	The expected duration and size of a release should be taken into account selecting radiation threshold, most relevant hydrogen jet fires will be of limited extent and duration and higher thresholds may be acceptable.

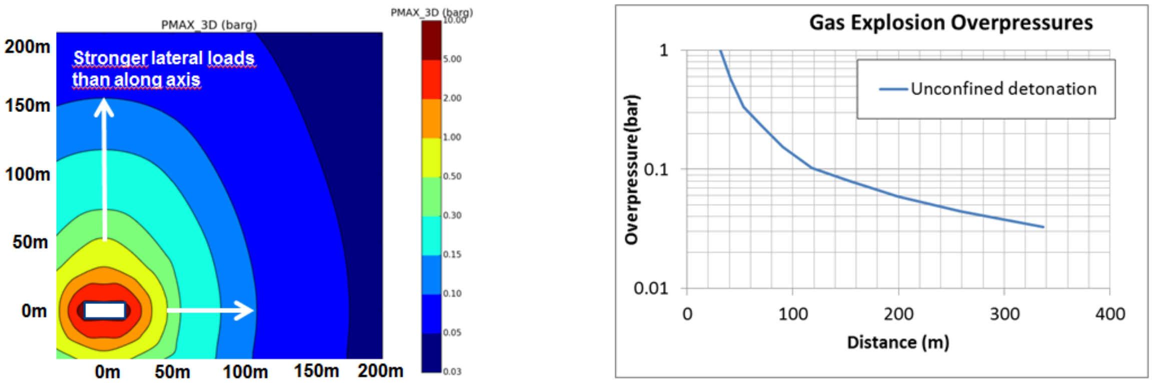

Figure 2: TNO Multienergy method (LR tool-right) can provide good blast estimates quickly. CFD calculations (FLACS-left) can provide better precision taking source, buildings or target characteristics into account.

3. Risk assessment examples

3.1 Hydrogen refuelling stations

The design of hydrogen refuelling stations is generally optimized with risk in mind. Fuel lines are generally protected and significant releases from dispensers shall be immediately detected by pressure losses and stopped, the layout is further very open to limit any accumulation of hydrogen. Nearby there would normally be outdoor high pressure hydrogen storage, and containers with compressors and processing for fuelling, and often production units. For these units loss of containment scenarios may take place. Jet- and flashfire risk can be minimized by vertical fireproof walls surrounding outdoor leak sources, this leaves a marginal residual risk from lateral radiation above the fences. Scenarios of some concern include potential high pressure tank rupture, see discussion in next section, and gas accumulation and explosions inside enclosed containers. For the expected release rates explosions from releases into the open mostly have limited consequences and contributions to risk is marginal. Based on the scenarios discussed with release frequencies from equipment counts and consequences estimated with LR screening tool and in some cases CFD, individual fatality risk contours of 10^{-5}/y, 10^{-6}/y and 10^{-7}/y are estimated for permitting purposes. For a refuelling station the contours will usually not be extensive. One advantage with this approach rather than safety distance table approaches is that this is more flexible for situations where the refuelling station includes dispensers and systems for other fuels, or there are other special features of the station.

3.2 Hydrogen fast passenger ferry

A main source for emissions within public transportation in Norway is the coastal transport, in particular the fast passenger ferries. There are currently several initiatives to develop zero emission hydrogen fuelled fast ferries, a concept risk assessment for one of these was performed as part of the MoZEES project, see Hansen (2018). In the risk assessment the various hydrogen systems were considered, including high pressure tanks, high pressure pipes/equipment, low pressure pipes, fuel cells and gas mast. The IGF-code, alternative design option, IMO (2017), was basis for the risk assessment, and equivalent safety level to conventional fuelled systems was to be demonstrated. All hydrogen systems were planned installed at the upper deck, thus any hydrogen release would disperse upwards once release momentum is lost. With vertical fences surrounding all open leak points so that any open release scenario will impinge and get diverted upwards, the risk from jet- and flashfires will be limited. If dimensions of all pipes and inventories are minimized this will limit the maximum hydrogen release rates and possible explosion consequences. From the initial assessment the main concern would be possible scenarios leading to catastrophic rupture of the high pressure tanks, this was assessed more in detail. Due to the high speed of sound for hydrogen the blast from such events will be significantly stronger than if a similar rupture took place in a tank of pressurized air or hydrocarbon gas. If the hydrogen is ignited during the release even stronger overpressures would be expected.

There are many open questions regarding high pressure tank ruptures, is the scenario credible, can catastrophic burst really happen, or will the failure mode rather be a less dangerous large release? For risk assessments considering credible scenarios only, rupture scenarios are seldom considered. Relevant failure frequencies for such incidents may be in the 10^{-7}/y to 10^{-6}/y-range. Since the global experience (# high pressure hydrogen tank years) is much less than 1 million, it is hard to justify lower failure frequencies based on experience. For probabilistic risk studies aiming to estimate 10^{-6}/y and 10^{-7}/y fatality risk contours these scenarios should be considered.

For fast passenger ferries 500 kg hydrogen at 250-350 bar may be stored on top of the vessel, likely in composite tanks to limit weight. Number of tanks may vary, several smaller tanks may increase the rupture scenario frequency significantly while the potential consequences are only moderately reduced (blast distance ~ cubic root of energy). Engulfing fires may be one of the main hazards which could lead to tank rupture, and mitigation methods include fire protection of tanks and pressure reduction by venting to gas mast. For the large quantities of gas considered venting will take time. For vent rates above 1 kg/s one might risk windows breaking in the harbour if gas plume would ignite, and this would not be acceptable consequence from initiating a safety measure. With an initial venting rate of 0.5 kg/s it would take 30 minutes to reduce tank inventory from 500 kg to 100 kg, and still the consequences from a rupture could be significant. For this type of scenario it will be necessary to identify maximum acceptable vent rate and thereafter ensure protection of the tanks against fire (external or from other tanks) to maintain integrity until sufficiently depressurized.

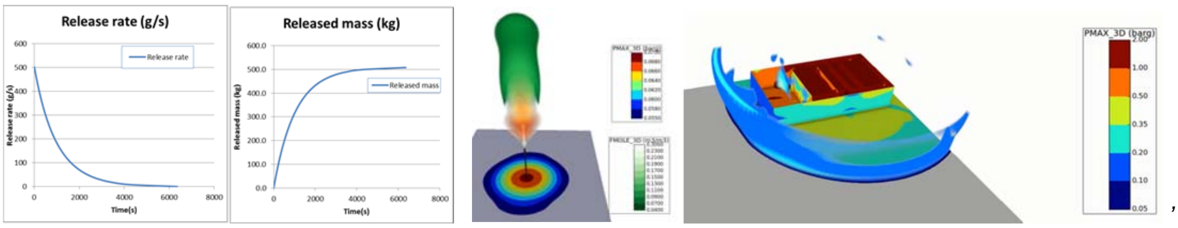

Figure 3: Release rate and mass for initial venting of 500 g/s from a 500 kg tank system (LR-tool left), predicted explosion during venting (400 g/s- middle), and blast from vessel burst simulated with CFD (right).

3.3 Liquid hydrogen handling

A scale up of the use of hydrogen e.g. for maritime applications, will likely require using liquid hydrogen. LH2 is currently only produced at a few locations in Europe, and will only be shipped to a limited number of countries. To facilitate large scale use of hydrogen there is a need for LH2 production facilities, LH2 needs to be transported and bunkered, and to be kept safely on board of a vessel while in operation. In all these processes there is a possibility for loss of containment of LH2. With a release of LH2 the hydrogen will immediately extract heat from surroundings, usually surrounding air, and evaporate. While evaporated hydrogen in itself is almost neutral buoyancy relative to ambient air, the surrounding air has been cooled, and the combined plume of hydrogen and cold air will be significantly denser than ambient air. For risk assessments the dense gas behaviour is important and hazard distances from LH2 releases will be many times longer than for gaseous hydrogen and LNG releases. LNG and LH2 will release about the same amount of gas from a given hole size and pressure based on combustion energy. The energy density at LFL for LH2 is however four times lower, and flammable gas dispersion distances become much longer with LH2 even with assumption of full flashing of LNG, see Figure 4. For risk studies with potential for LH2 releases hazard distances from LH2 releases will tend to give the longest hazard distances, justifying more detailed studies.

Figure 4: Road tanker release from 10 bar and ¼" hole, flammable cloud for LNG (left) and LH2 (right)

3.4 Hydrogen processing inside buildings

Due to climate or practical considerations it is not always feasible to process hydrogen outdoor. With indoor processing there may be a risk for accumulation of significant, reactive gas clouds with potentially severe consequences if ignited. For such situations there is a particular need to enhance the screening risk assessment with more detailed CFD-calculations to support the design process by giving advice to minimize the risk for dangerous accumulation of gas. Work should focus on minimizing the probability for significant releases (pipe diameters, flow restrictions, inventory sizes), efficient leak detection, rapid shut-down and depressurization, efficient ventilation and design of building. A tall building will generally see lower concentrations accumulating near ceiling than a low building, and optimized design, detection and efficient emergency venting can help limit the accumulation of hydrogen at reactive concentrations. If significant hydrogen clouds at concentrations above 20% may accumulate and ignite, the risk for transition to detonation can be significant, with total destruction of building and strong blastwaves breaking windows several hundred meters away. If concentrations can be kept mostly below 15% much less severe explosion scenarios would be expected. The more detailed CFD study can help optimize design and mitigation measures to limit the frequency and potential consequences of damaging explosions.

4. Conclusions

An increasing use of hydrogen is initiated in the society with pressurized hydrogen systems planned in homes, cars and as fuel for public transportation. Considering the potentially extreme explosion properties of hydrogen it is important that this introduction of hydrogen is done in a safe way, and that systems are designed with safety in focus so that severe accidents are prevented. This article presents experiences and perspectives from hydrogen system risk assessments. Most systems considered can be designed with low risk to surroundings, provided simple safety principles are followed, often simple screening analyses will be sufficient to confirm acceptable risk level. For situations with possible significant gas accumulation inside buildings or confinements particular care must be taken to prevent severe explosions. Systems handling liquid hydrogen should also be given particular attention as releases will show dense gas behaviour and hazard distances may be longer than for gas phase hydrogen. For these situations more detailed CFD-assessments may be required to optimize design and quantify risk. By following certain design principles, and giving particular attention to challenging scenarios discussed in this article, a safe handling of hydrogen should be possible.

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